

Tests of the fundamental symmetries in η meson decays

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Abstract. Patterns of chiral symmetry violation and tests of the conservation of the fundamental C , P and CP symmetries are key physics issues in studies of the π^0 , η and η' meson decays. These tests include searches for rare or forbidden decays and searches for asymmetries among the decay products in the not-so-rare decays. Some examples for the rare decays are $\eta \rightarrow 2\pi$, $\eta \rightarrow 4\pi^0$ (CP tests), decays into an odd number of photons (*e.g.*, $\eta \rightarrow 3\gamma$) and the decay $\eta \rightarrow \pi^0 e^+ e^-$ (C tests). In the conversion decay $\eta \rightarrow \pi^+ \pi^- e^+ e^-$, the asymmetry in the distribution of the angle between the two-pion and two-lepton decay planes allows to search for CP violation in a flavor-conserving process beyond the CKM mechanism which is not constrained by the limits on the neutron dipole moment. In addition, the Dalitz decays and the decays into a lepton-antilepton pair are sensitive to contributions from a vector boson responsible for the annihilation of hypothetical light dark matter particles. The muon $g - 2$ and the branching ratio for the $\pi^0 \rightarrow e^+ e^-$ decay are currently the observables where hints of a deviation from the Standard Model predictions are reported. The experimental studies of the π^0 , η and η' meson decays are carried out at four European accelerator research facilities: KLOE/KLOE-2 at DAFNE (Frascati), Crystal Ball at MAMI (Mainz), WASA at COSY (Jülich), Crystal Barrel at ELSA (Bonn).

1. Introduction

The π^0 , η and η' mesons belong to the longest living hadrons decaying predominantly via electromagnetic or strong processes that are eigenstates of parity (P) and charge conjugation (C) operators. They therefore allow for studies of the (non)-conservation of the C , P and CP symmetries in strong and electromagnetic interactions. In the case of the π^0 and η meson all the strong and electromagnetic decays are either forbidden or at least severely suppressed. Nevertheless, there exist many open (energetically allowed) final states for the η and η' meson decays, such that a variety of symmetry tests is possible.

The most probable decays of the η meson are [1]: the second order electromagnetic decay into two photons ($\text{BR} \approx 39\%$), which is driven by the chiral (triangle) anomaly, and the isospin-violating decays into three pions ($\eta \rightarrow \pi^0 \pi^0 \pi^0$ @ $\text{BR} \approx 33\%$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ @ $\text{BR} \approx 23\%$), which are mainly due to the difference between the u and d quark masses since electromagnetic contributions are suppressed. The first order radiative decay $\eta \rightarrow \pi^+ \pi^- \gamma$ ($\text{BR} \approx 5\%$) is also induced by the chiral anomaly.

Any radiative decay with one or more photons in the final state is accompanied by a process where the photon converts internally into a lepton-antilepton pair [2]. The conversion decays allow to study the *transition form factors* describing the structure of the interaction region. The form factors are also measured in the $\gamma^*\gamma^* \rightarrow \eta$ processes in e^+e^- colliders. The precise knowledge of the transition form factors of the π^0 and η mesons is needed for the calculations of the Standard Model (SM) contributions to the muon $g - 2$ and to the rare π^0 and η meson decays into a lepton-antilepton pair.

2. Tests of CP symmetry

Most of the tests of the CP symmetry in η decays are modeled as flavor conserving counterparts of the corresponding K_L decay modes. The straightforward test is to search for P and CP violating η decays into two pions. The best experimental limits are from KLOE [3], $\text{BR}(\eta \rightarrow \pi^+\pi^-) < 1.3 \cdot 10^{-5}$, and GAMS-4 π [4], $\text{BR}(\eta \rightarrow \pi^0\pi^0) < 3.5 \cdot 10^{-4}$. The theoretical branching ratios are very small [5]: in the SM, the decays are G_F^2 processes additionally suppressed by a cancellation of nearly equal terms leading to the branching ratio estimate $\text{BR}(\eta \rightarrow \pi\pi) \leq 2 \cdot 10^{-27}$. The branching ratio generated by a CP violation in the extended Higgs sector of the electroweak theory is listed in [6] as $\text{BR}(\eta \rightarrow \pi^+\pi^-) = 2\text{BR}(\eta \rightarrow \pi^0\pi^0) \leq 1.2 \cdot 10^{-15}$. If strong interaction physics via the θ term were the culprit for the CP violation, the empirical bound [1] on the electric dipole moment of the neutron would limit the pertinent branching ratio to $\text{BR}(\eta \rightarrow \pi\pi)_\theta \leq 3 \cdot 10^{-17}$. In fact, as argued by Gorchtein [7] the bound on the electric dipole moment of the neutron can be used to impose a limit on the branching ratio $\text{BR}(\eta \rightarrow \pi\pi) \leq 3.5 \cdot 10^{-14}$ no matter what the underlying CP violating mechanism would turn out to be.

The search for the barely (energetically) allowed η decay into $4\pi^0$, proposed by Nefkens [8], see also Ref. [9], represents a new kind of CP test with no analog in the K_L system. If all the final pions are in relative s waves, the decay is forbidden by P and CP invariance. Due to the very low excess energy of 7.9 MeV this assumption seems to be plausible. However, CP can be conserved if the final state involves higher partial waves than s or p waves. Therefore it is interesting to consider the analogue $\eta' \rightarrow 4\pi^0$ decay where the phase space is big enough for the four pions to group into two d -wave pion pairs which can couple to a combined angular momentum of $0^+, 1^+, \dots, 4^+$. If furthermore the two pairs are then in a relative p -wave state, *i.e.* if the orbital angular momentum between the pairs is 1^- , the full four-pion system can be in a pseudoscalar $J^{PC} = 0^{-+}$ state.

Since an odd number of (quasi)-Goldstone bosons is involved, the decay is driven by the chiral anomaly or, more precisely, by a higher order term (than the fourth order of the Wess-Zumino-Witten action) of the intrinsic-parity-odd sector of Chiral Perturbation Theory, see *e.g.* [10, 11]. Note that the simple flavor structure together with the Bose symmetry of the pions excludes a direct contribution of the pentangle anomaly. For the same reason, also the decay path $\eta^{(\prime)} \rightarrow \rho^0\rho^0 \rightarrow (\pi^0\pi^0)(\pi^0\pi^0)$ is forbidden. In fact, as shown in [12], even direct contributions of chiral order $\mathcal{O}(p^6)$ Lagrangians tabulated in [10, 11] and, moreover, direct and indirect $\mathcal{O}(p^8)$ contributions can be excluded, such that chiral order $\mathcal{O}(p^{10})$ processes come into play: *e.g.*, a triangle-anomaly decay into two rho mesons (which, in fact, is already of $\mathcal{O}(p^6)$) plus (at least) one additional d -wave pion loop/rescattering of order $\mathcal{O}(p^4)$ or a direct process via two isoscalar f_2 tensor-mesons, $\eta^{(\prime)} \rightarrow f_2f_2 \rightarrow (\pi^0\pi^0)(\pi^0\pi^0)$, which is of chiral order $\mathcal{O}(p^{10})$ [12], see Figure 1.

Using naive phase space arguments the CP allowed 4-pion decays can be estimated – at least close to threshold – to scale as $(pr_0)^{1+3+3+2\cdot 2+2\cdot 2+2\cdot 1} = (pr_0)^{17}$ where p is the averaged three-momentum modulus of a π^0 in the η, η' center-of-mass frame and $r_0 \sim 1/m_\rho$ is the effective range of the interaction between two pions expressed by the ρ -meson mass. This predicts a tiny ratio of the partial widths $\Gamma(\eta \rightarrow 4\pi^0)/\Gamma(\eta' \rightarrow 4\pi^0) \leq 10^{-16}$. The estimates of the branching ratio limits, however, have to involve the comparison with other decay channels (*e.g.* $\eta \rightarrow \pi^0\pi^0\pi^0$,

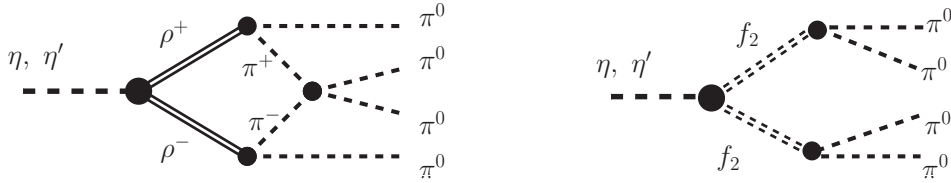


Figure 1. (Left) An example of an anomaly-driven pion-loop/rescattering diagram contributing to the CP allowed $\eta/\eta' \rightarrow 4\pi^0$ decay. Note that to the left of the rescattering vertex the $\pi^\pm\pi^0$ pairs resulting from the vector mesons are p -wave states, whereas to the right of the vertex the upper and lower (or inner and outer) $\pi^0\pi^0$ pairs have to be d -wave states. Nevertheless, the overall angular momentum is always $J^{PC} = 0^{-+}$ because of the relative p -wave orbital angular momentum between the two vector mesons and between the upper and lower (inner and outer) $\pi^0\pi^0$ pairs. (Right) Direct decay $\eta^{(\prime)} \rightarrow f_2 f_2 \rightarrow (\pi^0\pi^0)(\pi^0\pi^0)$ where the two virtual isoscalar d -wave bosons f_2 are emitted in a relative p -wave state. Both processes are of order $\mathcal{O}(p^{10})$ [12].

$\eta \rightarrow \pi^+\pi^-\ell^+\ell^-$, $\eta' \rightarrow \pi^0\pi^0\eta$ etc.) and are more uncertain: $\leq 10^{-10}$ for the η and (with more caveat because of the increased distance to the threshold) $\leq 10^{-8}$ for the η' . A measurement of a non-zero BR for these $\eta/\eta' \rightarrow 4\pi^0$ decays above the specified limits would probably be a signal for a CP violating process.

Experimentally the main advantage of the decay is the very low background from the direct pion production if the experiment is carried out in η meson production reactions close to threshold. In fact, the experimental limit obtained by the Crystal Ball collaboration [9], namely the $BR < 6.9 \cdot 10^{-7}$, is the most sensitive result on any of the η meson decays. As mentioned above, an interesting possibility is to search for the $\eta' \rightarrow 4\pi^0$ decay. The experimental limit on the BR is $5 \cdot 10^{-4}$ from the GAMS-2000 spectrometer [13].

The search for linearly polarized photons in the $\eta \rightarrow \pi^+\pi^-\gamma$ decay was proposed by Geng and collaborators [14]. As this process is flavor-conserving and involves an extra photo-production vertex, the sensitivity of this CP test is not constrained by the experimental limits on the $\eta \rightarrow \pi\pi$ decays or the electric dipole moment of the neutron or by CP violating processes in the flavor changing kaon and B -meson sectors. The practical realization of this idea is to investigate the $\eta \rightarrow \pi^+\pi^-e^+e^-$ process [15]. The violation of the CP symmetry in the $\eta \rightarrow \pi^+\pi^-e^+e^-$ decay would manifest itself as an angular asymmetry between the pionic and the lepton-antilepton decay planes. In the case of the $K_L \rightarrow \pi^+\pi^-e^+e^-$ decay such an asymmetry [16, 17, 18] is driven by standard CKM mechanism and it was observed by the KTeV collaboration [19] and the NA48 collaboration [20]. In the case of the η system a possible mechanism leading to such an asymmetry could be the interference between the usual CP allowed magnetic M_1 transition (driven by the chiral anomaly) and a CP violating flavor-conserving electric dipole operator [14] which is sensitive to the strange quark content of the decaying η meson and which is not constrained by SM physics. The experimental bound on this asymmetry, measured by the KLOE collaboration, is still compatible with zero, $A_\phi = (-0.6 \pm 3.1) \cdot 10^{-2}$ [21].

3. Tests of C symmetry

There exists only limited knowledge of the C -symmetry (non-)conservation in strong and electromagnetic interactions. Any η decay into *neutrals* with an *odd* number of photons in the final state will not conserve C . The simplest example of this class is the decay into three photons which, however, is heavily suppressed: each photon pair has to involve at least two units of angular momentum because of gauge invariance and Bose symmetry [22, 23]; the case of a photon pair with total angular momentum zero is excluded, since it would correspond to a

radiative $0 \rightarrow 0$ transition, which is forbidden for a real photon [24], while the case of a photon pair with total angular momentum $J = 1$ is in conflict with Bose symmetry [25]. The present upper limit from the KLOE experiment is $\text{BR}(\eta \rightarrow \gamma\gamma\gamma) < 1.6 \cdot 10^{-5}$ 90% CL [26].

Also the η decays into π^0 mesons and an odd number of direct photons belong to the above-mentioned class. The simplest prototype would be the $\eta \rightarrow \pi^0\gamma$ decay which, however, as a radiative $0 \rightarrow 0$ transition with a real photon is absolutely forbidden by angular momentum conservation [24]. The experimental bound on this decay from the Crystal Ball collaboration is $\text{BR}(\eta \rightarrow \pi^0\gamma) \leq 9 \cdot 10^{-5}$ [27]. The next simplest cases are then the decays with more than one π^0 but only one photon in the final state: $\eta \rightarrow \pi^0\pi^0\gamma$ and $\eta \rightarrow 3\pi^0\gamma$. The best branching ratio limits for these decays come again from the Crystal Ball experiment and are $5 \cdot 10^{-4}$ and $6 \cdot 10^{-5}$, respectively [28].

In addition, η decays into neutrals plus an odd number of dilepton pairs in the final state as, *e.g.*, the decay $\eta \rightarrow \pi^0 e^+ e^-$ may be used for tests of charge conjugation invariance. The main SM contribution to this process (shown in Figure 2) comes from the C -conserving exchange of two intermediate photons ($\eta \rightarrow \pi^0 \gamma^* \gamma^* \rightarrow \pi^0 e^+ e^-$) with a branching ratio of about 10^{-8} [29]. The process with one virtual photon γ^* in the intermediate state is forbidden by C symmetry

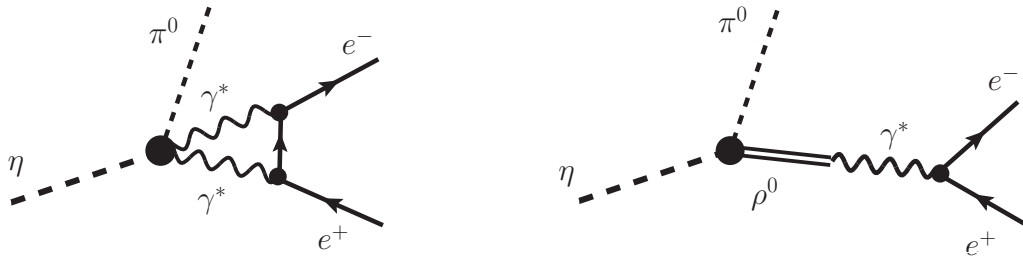


Figure 2. (Left) Fourth-order electromagnetic C -conserving transition: $\eta \rightarrow \pi^0 \gamma^* \gamma^* \rightarrow \pi^0 e^+ e^-$. (Right) Diagram for a possible C -violating process: $\eta \rightarrow \pi^0 \rho \rightarrow \pi^0 e^+ e^-$.

and, moreover, has to have a vanishing transition form factor in the on-shell limit, since – as stated above – the direct $\eta \rightarrow \pi^0\gamma$ vertex is forbidden by angular momentum conservation [24].

At present, the empirical upper limit for the $\text{BR}(\eta \rightarrow \pi^0 e^+ e^-)$ is equal to $4.5 \cdot 10^{-5}$ 90% CL, which comes from an 1975 experiment [30]. The data used for obtaining this limit were analyzed under assumption of a constant decay matrix element and a cut $M(e^+ e^-) > 140$ MeV was applied. For the analog decay $\eta \rightarrow \pi^0 \mu^+ \mu^-$, there exists a similar branching ratio limit, $\text{BR}(\eta \rightarrow \pi^0 \mu^+ \mu^-) < 5 \cdot 10^{-6}$ [31]. Furthermore, also the single-photon contributions to the η' decays into a π^0 or η pseudoscalar and a dilepton pair ($e^+ e^-$ or $\mu^+ \mu^-$) belong to the class of C -violating processes.

Finally, the C invariance can be tested also in, *e.g.*, $\eta \rightarrow \pi^+ \pi^- \gamma$ and $\eta \rightarrow \pi^+ \pi^- \pi^0$ decays where it can manifest itself as an asymmetry in the energy distributions for π^+ and π^- mesons in the rest frame of the η meson [32, 33]. The asymmetries in the $\eta \rightarrow \pi^+ \pi^- \gamma$ and $\eta \rightarrow \pi^+ \pi^- \pi^0$ decays were investigated in a few experiments in the 1970s [34, 35, 36, 37, 38]. For the $\eta \rightarrow \pi^+ \pi^- \pi^0$ asymmetries there exist recent limits from the KLOE collaboration with sensitivity 10^{-3} [39].

4. Dark force searches

The rare decays of a neutral pseudoscalar meson P (π^0 , η or η') into one dilepton pair ($e^+ e^-$ or, if kinematically allowed, $\mu^+ \mu^-$) belong to the most interesting processes of low-energy hadron physics, since the SM calculation predicts minuscule tree-level contributions (via a

virtual Z boson), such that a window of opportunity for the admixture of physics beyond the standard model might open up as the rates are small. In fact, the relative branching ratio $\text{BR}(P \rightarrow l^+l^-)/\text{BR}(P \rightarrow \gamma\gamma) \sim (\frac{\alpha}{\pi} \frac{m_l}{m_P})^2$ is not only suppressed by two powers of the fine-structure constant α resulting from the coupling of *two* virtual photons to the dilepton pair, but also by the helicity mismatch of the two outgoing leptons – indicated by the squared ratio of the lepton mass m_l to the pseudoscalar mass m_P . Recently the KTeV collaboration determined a new precise value of the branching ratio $\text{BR}(\pi^0 \rightarrow e^+e^-) = (7.49 \pm 0.29 \pm 0.25) \cdot 10^{-8}$ which exceeds the up-to-date theoretical calculations by Dorokhov *et al.* [40, 41, 42] by 3 standard deviations.

Kahn and collaborators [43] suggested as a possible explanation of this excess the tree-level exchange of an off-shell neutral vector boson U (pioneered by Fayet [44, 45]) of mass $m_U \sim (10 - 100)$ MeV. The latter is of the type proposed in the light dark matter models by Boehm *et al.* [46, 47, 48, 49] (see also Ref. [50]) to mediate the annihilation reaction $\chi\chi \rightarrow e^+e^-$ of a neutral scalar dark matter particle χ of $(1 - 10)$ MeV mass, such that the excess positrons produced in this annihilation reaction could account for the bright 511 keV line emanating from the center of the Galaxy [43].

In order to explain the mismatch between experiment and theory for the branching ratio $\text{BR}(\pi^0 \rightarrow e^+e^-)$, Kahn *et al.* [43] assumed that the neutral vector meson U would couple to the u and d quark fields of the π^0 and the e^+e^- dilepton pair via the axial-vector components g_A^u , g_A^d and g_A^e , respectively, where – for simplicity – a common axial coupling $g_A \equiv g_A^u - g_A^d \equiv g_A^e$ of the order of $g_A = (2.0 \pm 0.5) \cdot 10^{-4} \cdot m_U/(10 \text{ MeV})$ was fitted. In fact, the computation of the partial width of this process is modeled according to the analog SM tree-level process $\pi^0 \rightarrow Z^* \rightarrow e^+e^-$, where the Z -boson mass m_Z is replaced by the much lighter mass m_U and where the weak coupling is replaced by $g_A^{u,d,e}$. Assuming that the octet axial-vector quark-coupling is of the same order as above, the U boson contribution to the branching ratio $\text{BR}(\eta \rightarrow e^+e^-)$ is about 10^{-9} , which is of the same order as the estimates of Dorokhov [40, 41, 42] and much smaller than the experimental bound $2.7 \cdot 10^{-5}$ of the CELSIUS/WASA collaboration [51]. The same fit, however, predicts a contribution of order $2.0 \cdot 10^{-5}$ to $\text{BR}(\eta \rightarrow \mu^+\mu^-)$ which is nearly an order of magnitude larger than the measured value $\text{BR}(\eta \rightarrow \mu^+\mu^-) \sim (5.7 \pm 0.9) \cdot 10^{-6}$ [52], unless the axial-vector coupling of the U meson to the muon is smaller than g_A^e or the octet axial-vector quark coupling is smaller than $g_A^u - g_A^d$ or both. This is of course a limitation in the predictive power of the U boson exchange mechanism.

Another variant of a dark matter U gauge bosons, the a_μ , was suggested by Reece and Wang [53] (see also the work by Fayet [54, 55, 56, 57]): here the additional $U(1)_d$ ‘dark’ gauge boson couples to the SM $U(1)$ gauge boson by a gauge kinetic mixing term $\mathcal{L}_{\text{kin-mix}} = -2\epsilon F^{\mu\nu} F_{\mu\nu}^d$ with a strength $\epsilon \sim 10^{-3}$ or less. The dark $U(1)_d$ group is assumed to be spontaneously broken by the introduction of a dark higgs h_d field which acquires a GeV scale vacuum expectation value, such that $m_U \sim 1 \text{ MeV} - \text{few GeV}$. Under a field redefinition to the standard massless photon, the U boson couples *vectorially* to all SM charged fields as $\epsilon a_\mu J_{\text{EM}}^\mu$, where J_{EM}^μ is the pertinent SM electromagnetic current of the particle. In addition, the U -boson also couples to SM weak neutral currents; however, the corresponding coupling is suppressed by a factor of order m_U^2/m_Z^2 . Therefore, this U boson variant has very small axial couplings to SM matter fields and cannot serve as a candidate for fitting the missing excess in the $\pi^0 \rightarrow e^+e^-$ decay.

First searches for U bosons of the Reece and Wang type are on the way. The relevant channels are, *e.g.*, the decays $\phi \rightarrow \eta U$, $U \rightarrow e^+e^-$ and $\eta \rightarrow \gamma U$, $U \rightarrow e^+e^-$. A signature for a U boson would be a peak in the pertinent Dalitz decay $\phi \rightarrow \eta e^+e^-$ or $\eta \rightarrow \gamma e^+e^-$, while the background for such searches is the standard Dalitz decay. The searches for U bosons in the $\phi \rightarrow e^+e^- \eta$

conversion decay are carried out by KLOE collaboration¹.

Finally, as the above mention experiments will all aim at searching for a narrow peak on a large conversion background, one should also mention an attractive alternative for U boson searches: the (C)-forbidden η decays, especially the decay $\eta \rightarrow \pi^0 e^+ e^-$, where both the conventional and the C -violating background are suppressed for low $M(e^+ e^-)$. From the background point of view it is an ideal process to search for a low energy U boson. From the theory point of view, however, one has to cope with the additional suppression by either the violation of C symmetry, which applies to the Reece-Wang U boson and to the Boehm *et al.* case under vector coupling, or by a violation of parity P in the Boehm *et al.* case under axial-vector coupling.

5. Experiments

The experimental programs for η and η' decays are on the agenda both at e^+e^- colliders and hadro- or photo-production fixed target experiments. Currently active experiments at e^+e^- colliders are KLOE-2 at DAΦNE [58] and BESIII at BEPC [59]: the η and η' mesons then result from radiative decays of ϕ or J/ψ mesons. The π^0 , η and η' mesons can copiously be produced in γp , pp or pd interactions not far from the production thresholds. The mesons originate from decays of nucleon isobars (for η mainly from $N^*(1535)$). There are two experiments which use the $\gamma p \rightarrow p\eta^{(\prime)}$ reaction close to threshold: Crystal Ball at MAMI [60] and Crystal Barrel at ELSA [61]. The $pp \rightarrow pp\eta$ reactions provides the highest useful rate of tagged η mesons enabling

Table 1. Production of η and η' mesons close to threshold; p_{thr} is the beam momentum at threshold; Q is the CMS excess energy corresponding to the maximum or optimal cross section (σ). The last column indicates the total inclusive cross section for a given initial state (σ_T). The data were extracted from references [62, 63, 64, 65, 66, 67, 68].

Reaction	p_{thr} [GeV/c]	Q [MeV]	σ	σ_T [mb]
$pp \rightarrow pp\pi^0$	0.777	122	1.3 mb	40
$pp \rightarrow pp\eta$	1.981	40	5 μb	40
$pp \rightarrow pp\eta'$	3.208	45	300 nb	40
$pd \rightarrow {}^3\text{He}\eta$	1.569	2	400 nb	80
$pd \rightarrow {}^3\text{He}\eta'$	2.434	60	1 nb	80
$\pi^- p \rightarrow n\eta$	0.684	36	2.6 mb	50
$\pi^- p \rightarrow n\eta'$	1.432	100	100 μb	35
$\gamma p \rightarrow p\eta$	0.706	60	16 μb	0.30
$\gamma p \rightarrow p\eta'$	1.447	40	1 μb	0.15

studies of the rare decays which have a distinct signature as, *e.g.*, the decay $\eta \rightarrow e^+ e^-$ where an integrated luminosity corresponding to 10^{10} η s is needed. The η and η' production in pp and pd interactions have the lowest ratio of the cross section to the total inclusive one. However, the signal-to-background ratio can be enhanced by working close to threshold at the price of a lower production cross section. The ideal reaction in this respect is $pd \rightarrow {}^3\text{He}\eta$, where the cross section rises very quickly, reaching a plateau already at an excess energy of about 1 MeV above threshold [63]. The presence of a doubly charged, heavy ${}^3\text{He}$ ion in the exit channel can easily be detected and thus provides a very efficient and high-purity trigger condition. Close to threshold the ions can be filtered using a magnetic spectrometer with the acceptance below one degree.

A feature of the close-to-threshold experiments is that particles from the production processes are emitted in a small forward cone. Their momenta can be identified and measured in a

¹ S. Giovannella in DISCRETE2010 proceedings.

dedicated detector which covers a limited range of scattering angles. The meson production is identified (tagged) by the missing mass. When the beam momentum is known precisely the missing mass is kinematically constrained close to threshold and the resolution depends weakly on the precision of the kinetic energy determination of the particles. For example at light-ion storage rings, the beam-momentum resolution is of the order of 0.1% FWHM and a pp missing-mass resolution of typically a few MeV/c^2 FWHM is achieved. The light decay particles are emitted more isotropically (since the velocity of the center of mass system is not very high) and their registration requires a detector with nearly 4π sr coverage. A typical resolution for the invariant masses of the decay products is a few ten MeV/c^2 . The clear separation of the phase space regions for tagging and decay particles in the close-to-threshold tagging helps, *e.g.*, in the determination of the absolute branching ratios $\Gamma_i/\Gamma_{\text{tot}}$.

There are three detectors which have started a second round of $\eta^{(\prime)}$ decay experiments: Crystal Ball, Crystal Barrel and WASA. The Crystal Ball and Crystal Barrel detectors are now used for $\gamma p \rightarrow \eta^{(\prime)} n$ experiments. The third detector, WASA, was build at TSL Uppsala where η decay experiments were carried out in pp and pd interactions until 2005 at the CELSIUS light ion storage ring.

The design of the Crystal Ball [69], Crystal Barrel [70] and WASA [71] detectors is similar. The main part consists of a multi-segmented calorimeter of NaI, CsI(Tl) and CsI(Na), respectively. The detectors are compact enough so that they can be transported to other accelerators. In the present configuration the Crystal Ball and Crystal Barrel set-ups are extended by forward calorimeters consisting of BaF_2 crystals from the TAPS setup [72]. On the other hand they have limited capabilities for a measurement of charged decay products.

WASA is the most complicated of the three detectors. It includes a novel pellet target system allowing for low background and wide angle detection. The design of the detector was optimized for $\pi^0, \eta \rightarrow e^+e^-$ decays. In addition to the electromagnetic calorimeter, the central part of the detector includes a superconducting solenoid and a cylindrical mini drift chamber (MDC) with 17 layers of thin-walled ($25\mu\text{m}$) aluminized mylar tubes. The complete detector system was transported to the Forschungszentrum Jülich in 2005, installed at COSY storage ring, and it was operational already after one year [73]. The relocation of the detector had strengthened the experimental programme since COSY allows for higher energy beams (up to above $pp \rightarrow pp\phi$ threshold) and for polarization. The detector system was upgraded with a completely new readout system, the refurbishing of old scintillator elements, and an extension of the forward part of the detector for the higher energies. The maximum useful luminosity of the facility is about $10^{32}\text{cm}^{-2}\text{s}^{-1}$.

KLOE-2, WASA-at-COSY and Crystal Ball aim at a significant improvement of the sensitivity of the discrete symmetries tests in the decays of the η and η' mesons beyond the presently achieved limits. With an expected number of about $10^9 - 10^{10}$ η mesons tagged, a significant improvement is expected. In the nearest future, WASA-at-COSY will provide an order of magnitude improvement of the branching ratio limit for the $\eta \rightarrow e^+e^-$ decay and the first investigations of the $\eta \rightarrow \pi^0 e^+e^-$ decay in the low electron-positron invariant mass region, $M(e^+e^-) < 120 \text{ MeV}$. High statistics measurements of the π^0 meson decays are also planned. The KLOE-2 experiment at DAΦNE presented at this conference² is starting data taking and the goal is to collect about 10^9 η and 10^7 η' events. With regard to the perspectives of other experiments, one should not forget to mention the inclusive dimuon spectrum at 7 TeV from the CMS experiment (at 40 pb^{-1}), presented by G. Rolandi at this conference. The spectrum shows a clear $\eta \rightarrow \mu^+\mu^-$ peak and thus the feasibility of a precise BR measurement using the same technique as previously the NA60 experiment [74]. The first results on η' decays from the BESIII experiment were recently published [75].

² S. Miscetti in DISCRETE2010 proceedings.

Acknowledgments

The authors gratefully acknowledge discussions with Christoph Hanhart, Bastian Kubis and Feng-Kun Guo. This work was in part supported by the European Commission under the 7th Framework Programme through the ‘Research Infrastructures’ action of the ‘Capacities’ Programme: FP7-INFRASTRUCTURES-2008-1, Grant Agreement N. 227431.

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